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EMISSION FACTORS OF TRACE METALS FROM COAL-FIRED POWER PLANTS

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1 INTRODUCTION

One of the main problems facing the world of today is to secure a continuous supply of primary energy. In forecasts of power demand emphasis is focused on fossil fuels and especially on bituminous coal and lignite. However, coal-fired power plants may create a serious hazard to the environment. As a result of coal combustion, considerable amounts of gaseous substances and particulate matter are emitted into the atmosphere. The literature contains many references on airborne gases emitted by power plants and the problem itself is sufficiently well understood. This note, however, is devoted to the problem of environmental pollution by particulate emissions from coal-fired power plants. The main goal of this work is to establish emission factors of trace metals for different types of power stations, using enrichment factors of these pollutants in the flue gas stream and technological data on boilers and emission control installations.

2 MAJOR PHYSICAL COMPONENTS AND COAL REQUIREMENT FOR COAL-FIRED POWER PLANTS

The amount of trace metals emitted per unit quantity of fuel consumed depends on the combustion conditions and trace metal content of the fuel.

2.1 Combustion conditions

Trace metal emissions depend on the type of furnace and stack-gas cleaning equipment. Furnaces in common use include: stoker-fired,

cyclone furnace-fired and pulverized coal-fired units. Stokers are devices which feed the fuel onto a grate within the furnace. Stoker firing is only practical for small power plants (< 100 MWe). Cyclone furnaces burn crushed coal in a horizontal kiln. A high velocity stream of air is injected into the kiln tangentially to create a cyclonic flame pattern. With a pulverized coal system, the coal is pulverized to a powder, mixed with air, and then blown into the furnace.

With pulverized coal firing (dry ash unit), 80 per cent of the ash becomes entrained in the flue gases; the remaining 20% settles in hoppers at the boiler base from which it is removed for disposal. This level of fly ash in the flue gas is relatively high (compared to stoker and cyclone furnaces) due to the fact that pulverized coal is burned in suspension. The fly ash level is reduced to about 50 per cent for a pulverized furnace with a slag-tap capability. With cyclone furnaces, only 20 to 30 per cent of the total ash is entrained as fly ash (1).

There are four types of fly ash control systems: electrostatic precipitators, wet scrubbers, fabric filters and mechanical collectors. Electrostatic precipitators and wet scrubbers are the most widely used installations so that emission factors of trace metals are calculated for these control devices. The fly ash escaping from the precipitator (generally 1 per cent or less of the total) is smaller than 2 μm in size (2). High collection efficiences, ranging from 99 to 99.9 per cent, can be achieved with a low pressure drop through the precipitator and low power requirements (3). A wet scrubber removes fly ash particles from the flue gas by impaction (primarily effective for >1 μm particles),interception (primarily effective for 0.1 to 1.0 μm particles), and diffusion onto collector fine droplets (for <0.1 μm particles) (4). Venturi and moving-bed scrubbers are the mostly widely used wet scrubbers for power plant applications. Venturi scrubbers have a nominal efficiency of 99% (5). Particle collection efficiences are also high for moving-bed scrubbers, ranging from 98.7 to 99.9% (6).

2.2 Classification of coal

Coal is composed of a highly complex and heterogeneous group of substances and possesses a wide range of chemical and physical properties influencing trace element emission. One of the most commonly accepted methods of coal characterization is classification by rank, developed by the American Society for Testing and Materials (7). Classification by rank, which represents the progressive response of coal to pressure and/or heat during the metamorphic process (8), orders coals into a series ranging from lignite, at the lower end of the scale, through the various ranks of sub-bituminous and bituminous coals, to the anthracites at the upper end of the scale. The classification (Table 1) is based upon fixed carbon, volatility content, calorific content, and agglomerating characteristics of coal.

Table 1: Classsification of coals (8)

Class	Moisture, %	Fixed carbon limits[1], %	Volatile matter limits[1], %	Calorific value limits[2,3], Btu/lb
Anthracite	< 2	86-98	2-14	14.000-16.000
Bituminous	2-15	50-86	14-50	11.500-14.000
Subbituminous	20-30	40-60	-	8.300-11.500
Lignite	30-50	<40	-	6.300- 8.300

1 - Dry mineral matter-free basis

2 - Moist mineral matter-free basis

3 - To convert Btu/lb to J/kg, multiplying by 2.324×10^3

Bituminous coals, sub-bituminous coals and lignite are commonly used in power plants, so that the trace metal emission factors are estimated for these kinds of coal.

2.3 Coal required for power plant operation

The daily coal requirement (DCR) of a coal-fired electric power plant is given by (6):

$$DCR(\text{tonnes/day}) = \left(\frac{\bar{P}}{100}\right) \cdot C(\text{MWe}) \cdot 10^3 \frac{\text{kW}}{\text{MW}} \cdot 24 \frac{\text{h}}{\text{day}} \cdot 3412 \frac{\text{Btu}}{\text{kWh}} \cdot \frac{100}{E} \cdot \frac{1 \text{ lb coal}}{B_c \text{ (Btu)}} \cdot \frac{1 \text{ ton}}{2000 \text{ lb}} \cdot \frac{1 \text{ tonne}}{1.1 \text{ sh tn}} \qquad (1)$$

where: C = the noted capacity of the plant, in megawatts (MWe)

P = the capacity or plant factor, i.e., the percentage of capacity at which the plant operates, averaged over one year. A typical value for P is 70 per cent.

E = the efficiency of the plant, in per cent.

$\frac{E}{100}$ = kWh of electrical energy output from the plant per KWH of coal energy input into the plant. Typically E ranges from 36-40%.

B_c = the heat content, in Btu per pound of coal.

The daily coal requirements of the four model plants considered in this work are given in Table 2 for the three standard coal types..

Table 2: Daily coal requirements of the four model power plants burning three standard coal types.

Plant size (MWe)	Daily coal requirement, tonnes/day		
	Bituminous	Subbituminous	Lignite
100	495	600	834
350	1.730	2.100	2.920
700	3.460	4.200	5.830
2100	10.400	12.600	17.500

In Table 2, it was assumed that the plants use pulverized coal funaces, have a thermal efficiency of 38% and operate at 70 per cent capacity. It was also assumed, that the heat contents are following: For bituminous coal 13.85 Btu/lb, subbituminous 11.430 Btu/lb and liqnite 8220 Btu/lb. It is expected, that new coal fired plants will utilize pulverized coal firing rather

than cyclone furnaces. It should also be noted that daily coal requirements of power plants using cyclone firing is similar to daily coal requirements of plants using pulverized coal furnaces (9).

As can be seen from Table 2, larger quantities of lignite must be burned to equal the energy output of other ranks of coal because of the lowest carbon content, a relatively low heat content and the high value of moisture in lignite.

3 MINERAL MATTER AND TRACE ELEMENTS IN COAL

The term "mineral matter in coal" refers to mineral phases or species present in coal, and also to all chemical elements in coal that are generally found in the inorganic matter. More than 40 years ago, it was considered, that some elements in coal have either a high organic or inorganic affinity (10). Elements are generally described as: (1) associated with the organic fraction (2) mainly associated with the inorganic fraction, and (3) elements that could be associated with either or both fractions (11). Table 3 lists elements in order of decreasing affinity for the clean coal fractions or decreasing organic affinity (12).

Table 3: Affinity of elements for pure coal and mineral matter described by four authors (12).

Affinity	Davies	De Koven	Colchester	Herrin
Clean coal -lightest specific gravity fraction (elements in "organic combustion")	B Ge Be Ti Ga V Cr Sb Se Co Cu Ni Mn Zr Mo Cd	Ge Ga Be Ti Sb P Ni Cu Se Cr Mn Zn Zr V Mo Pb	Ge B P Be Sb Co Se Ga V Ni Pb Cu Hg Zr Cr Mn	Ge B Be Sb V Ga P Se Ni Cr Co Cu Ti Zr Pb Mn
Mineral matter (elements in "inorganic combustion")	Hg Pb Zn As	Hg As	As Mo Cd Zn	As Cd Zn Hg

It was found (13) that Br, Ge, Be, Sb, B and organic sulfur consistently fall in the organic phase. The sulfide-forming elements Zn, As, Cd, Fe, Zr, Hg, Pb, Hf, Mn and pyritic sulfur are consistently found mostly in the inorganic fraction. A number of other elements, Al, Si, Ti, V, Mo, K, P,Ga, Ca, Cr, Co, Ni, Cu, Mg, Se, are either intermediate in their association or highly variable. From among these P, Ga, Ti and V tend to be allied with the other elements having organic affinities, and Co, Ni, Cr, Se and Cu are more closely associated with the inorganically combined elements (14).

Trace metal emission data, used in this work to estimate the emission factors, include data on both organic and inorganic forms of elements.
From among more than 60 elements contained in the fuel, 16 are subject to analysis. They are as follows: As, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Sb, Se, V, Zn and Zr. They are either the most toxic to the environment, or appear at the highest concentrations in the fuel used. Table 4 shows general manifestations of these trace elements in animals.

Table 4: General manifestations of trace elements in animals (6).

Element	Target organs or characteristics of toxicity	Comments
Arsenic	Has been associated with increased incidence of lung cancer.	Non-accumulative in animals but has affinity for hair, nails, and skin.
Beryllium	Characteristic granulomatous changes of lung tissue is brought about by long-term exposure.	Via inhalation, beryllium is correlated with an interference in the passage of oxygen.
Cadmium	Is linked with the incidence of hypertension in experimental animals.	Accumulative in all animals and toxic to all systems and functions in humans and animals.
Cobalt	Causes changes in lungs typical of pneumoconiosis. Also causes induction of polycythemia in many species.	With increasing age, the body burden of cobalt diminishes.
Copper	Associated with induction of haemolytic disease, especially in certain species.	In excess, results in some accumulation in the tissue, especially in the liver.
Chromium	Hexavalent compounds extremely toxic to body tissue. Insoluble forms retained in lung tissue.	In particular, the respiratory tract and fat tissue accumulate this metal.
Lead	Newly absorbed lead is mostly retained in the body as lead triphosphate, especially in liver, kidneys, pancreas, and aorta.	Has strong affinity to accumulate in bone tissue.
Manganese	Acute intoxication involves changes in the respiratory system, whereas chronic poisoning affects the central nervous system.	Most amounts taken into the body are retained, especially in liver and lymph nodes.
Mercury	Organic forms have effects on brain tissue. The inorganic form is more linked to damage to liver and kidneys.	Can bioaccumulate in tissues of animals.
Molybdenum	Associated with degenerative changes in liver cells.	Can accumulate in tissues.
Nickel	Associated with cancer of lungs.	Very poorly absorbed from gut.
Selenium	Associated with alkali disease in cattle.	Is converted in the body into a volatile compound which is eliminated through breath and sweat.
Vanadium	Is found to inhibit the synthesis of cholesterol and other lipids. Other complications leading to cardiovascular diseases are also prevalent.	Vanadium salts are poorly absorbed from the gastrointestinal tract.
Zinc	Intoxication produces either lung or intestinal tract manifestations.	Absorbed or injected zinc is incorporated at varying rates into different tissue, indicating varying rates of zinc turnover.

Table 5 presents averaged concentrations of trace metals under study, estimated on the basis of literature data (6,9,15,16,17,18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29).

Table 5: Trace elements in coals.

Element	Bituminous µg/g		Subbituminous µg/g		Lignite µg/g	
	Range	Average	Range	Average	Range	Average
As	4.5-16.0	7.2	2.8-13.0	6.5	2.0-10.0	5. $
Be	0.6- 1.7	1.3	1.4- 1.7	1.5	0.9- 1.1	1.0
Cd	0.3- 1.8	0.47	0.4- 0.6	0.46	0.5- 2.1	0.61
Co	13.0-18.0	15.1	15.0-16.5	15.3	5.6-18.0	15.0
Cr	18.0-24.2	19.2	18.5-19.9	19.6	9.7-16.5	13.8
Cu	11.0,14.1	13.1	8.3- 9.7	8.9	4.4- 7.8	6.2
Hg	0.1- 0.3	0.2	0.1- 0.3	0.2	0.1- 0.3	0.1
Mo	5.2-11.0	7.8	3.4-11.0	7.1	2.2-11.5	7.0
Mn	19.0-41.0	26.0	26.5-46.1	31.0	9.7-25.8	19.8
Ni	16.0-25.0	18.0	8.8-14.5	11.5	13.5-15.5	15.0
Pb	3.7- 6.1	4.9	2.1-10.1	4.8	1.5- 9.6	4.7
Sb	4.0- 4.0	4.2	3.7- 3.9	3.8	3.6- 4.1	3.8
Se	2.4- 5.1	3.7	2.0- 4.0	3.0	0.8- 3.5	2.1
V	29.0-38.0	33.0	18.0-27.0	24.0	21.0-28.5	25.0
Zn	30.5-37.6	35.0	15.5-32.5	27.0	19.0-33.5	28.0
Zr	34.5-77.0	66.0	68.0-88.5	77.0	77.0-91.5	82.5

The concentration ranges will be smaller than those stated in Table 5, when the calculations of trace metal emission factors are made for power plants, burning coal from only one coal mine.

4 TRACE METAL BEHAVIOR DURING FUEL COMBUSTION

The processes occurring in a coal-fired boiler can be generalized as follows (pulverized coal taken as a example):

1. The coal is pulverized to particles with a mean diameter of 60 microns and a wide size distribution.
2. The coal is blown into the firebox with heated air through a burner.

3. The coal as burned in the firebox or radiant heat transfer section of the boiler. Typical peak temperatures are 1550°C. The temperature at the exit of the fire box is 1200-1500°C. Residence times of 1 to 2 seconds are required for complete combustion of the coal particles.

4. In the convective heat transfer sections, the temperature is reduced to 370-450°C during a residence time of several seconds.

5. The temperature is further reduced to 150°C in the air preheater.

According to theory (30,31,32), the volatile species in the ash are evaporated in the firebox and recondensed as submicron aerosol particles, or on the surface of ash particles as the flue gas cools in the convective sections. The concentrations of Pb, Sb, Cd, Se, As, Zn and Mo increase markedly with decreasing particle size, while Mn and Zr show little or no enrichment with decreasing particle size. The other elements, analysed in this work Be, Co, Cr, Cu, Ni and V, displayed an intermediate behavior. It was also found that 95 per cent of Hg contained in the coal is released through the stack as vapor (9,48,19). The enrichment process is stated mathematically as:

$$R_{ij} = \frac{m_{ij} / Al_j}{\sum_{j=2}^{n} m_{ij} \Big/ \sum_{j=2}^{n} Al_j} \qquad (2)$$

where:

R_{ij} is the enrichment ratio, relative to aluminium, of each element i in each outlet stream j,

m_{ij} is the mass flow rate of element i leaving in outlet stream j (j= 2,3,.... for n-1 outlet streams),

Al_j is the mass flow rate of aluminium in the jth outlet stream.

The summation terms in the denominator represent the total mass of element i and aluminium in the various outlet streams. Aluminium was chosen as the reference element because of its nonvolatile nature at furnace conditions in the stable aluminosilicates, a major class of mineral matter contained in the coal

ash. The enrichment ratios of element under study are listed in Table 6 (9,17,19,22,23,29,31,32,33,34).

Table 6: Enrichment ratios of elements analysed.

Element	Enriched (Group I)		Intermediate behavior (Group II)		Non-enriched (Group III)	
	Range	Average	Range	Average	Range	Average
As	1.3-3.0	2.6				
Be			1.1-1.4	1.3		
Cd	1.8-2.6	2.2				
Co			1.0-1.5	1.2		
Cr			1.0-1.6	1.3		
Cu			1.1-1.5	1.3		
Hg	1.0-2.8	2.2				
Mn					0.7-1.0	0.8
Mo	1.5-3.9	3.0				
Ni			1.3-1.5	1.4		
Pb	1.9-6.2	4.1				
Sb	1.9-4.1	3.1				
Se	2.1-3.5	2.7				
V			0.8-2.0	1.1		
Zn	1.8-3.7	2.6				
Zr					0.7-0.9	0.8

Data from Table 6 present enrichment factors in stack dust relative to concentrations in coal.

Generally, the enrichment behavior of trace elements in coal combustion is determined by the physico-chemical properties of the elements (their chemical compounds occurring in the coal and combustion products), the nature of the coal-burning process, and the mechanisms governing the emissions from the control devices. Group I elements from Table 6 are considered chalcophiles, which form volatile species upon combustion. Group II elements showed definite enrichment on small particles, but not nearly as strongly as Group I elements. They are a mixture of lithophiles and cholcophiles and possess unique characteristics that account for their intermediate behavior. Group III elements are considered as lithophiles and are assumed to have been homogeneously incorporated into

the aluminosilicate-dominated fly ash matrix. Mercury undoubtedly volatilizes as the element, and is predicted to exibit a dependance of concentration on particle size.

A mathematical volatilization-condensation model (35,36) relates the bulk concentration of the particles to their diameter, matrix composition, surface layer thickness, and surface concentration. Investigations of surface layer composition suggest that the outermost layer on the surface of some fly ashes is composed chiefly of H_2SO_4, which permits surface condensation of certain trace elements (37). The presence of sulfuric acid on some particle surfaces may be the causative agent in post-combustion crystal formation of metal and/or ammonium sulfates, but how this crystal formation affects the physico-chemical form of the enriched elements has not been studied.

The knowledge of enrichment behavior of elements analysed during coal combustion permits establishing the concentrations of these constituents in the fine dust particles. Table 7 shows concentrations of trace metals under study in different size particles (9,16,20,21,23,28,32,38,39,40,41).

Table 7: Mean concentrations of trace metals in different size particles emitted during coal combustion.

Element	Concentration in µg/g of dust fraction				
	> 10 µm	3-10 µm	1-3 µm	0.5-1.0 µm	<0.5 µm
As	25.0	25.8	102.8	221.0	498.0
Be	3.7	9.8	12.7	16.9	27.8
Cd	9.0	11.5	26.0	100.0	178.0
Co	60.0	90.0	330.0	300.0	320.0
Cr	290.0	460.0	470.0	1500.0	1600.0
Cu	270.0	390.0	500.0	396.0	501.0
Hg	2.3	2.4	2.2	2.3	2.5
Mn	330.0	430.0	490.0	580.0	600.0
Mo	48.0	101.0	192.8	213.0	249.0
Ni	400.0	540.0	900.0	1000.0	700.0
Pb	160.0	320.0	500.0	580.0	650.0
Sb	29.0	62.0	76.0	90.0	101.0
Se	19.0	59.0	60.0	59.0	68.0
V	320.0	360.0	380.0	421.0	380.0
Zn	240.0	500.0	630.0	830.0	990.0
Zr	440.0	320.0	306.0	290.0	280.0

A further aim of this work was to estimate concentrations of trace metals in stack dust emitted from different boiler types equipped with an ESP, using data on mean concentrations of elements in different size particles (Table 7) and the percentage distribution of different size particles in stack dust. (Table 8).

Table 8: Assumed percentage distribution of different size particles in stack dust (42,43,44,45).

Boilers	Assumed percentage distribution of particles			
	< 1 µm	1-3 µm	3-10 µm	> 10 µm
Cyclone	9	37	21	33
Stoker	4	10	36	50
Pulverized	10	22	28	40

Using data from Tables 7 and 8, the concentrations of trace metals in stack dust, emitted during coal combustion in different boilers, were calculated. The results are presented in Table 9.

Table 9: Concentrations of trace metals in stack dust, emitted during coal combustion in different boilers. (Power plants were ESP equipped).

Element	Concentration in µg/g			Element	Concentration in µg/g		
	Cyclone	Stoker	Pulverized		Cyclone	Stokes	Pulverized
As	100.73	59.19	95.24	Mo	130.80	89.60	114.80
Be	10.50	7.76	9.79	Ni	641.40	512.40	579.20
Cd	31.03	18.36	30.34	Pb	363.50	271.20	328.60
Co	189.60	108.20	151.60	Sb	59.80	48.46	55.78
Cr	510.20	421.60	508.20	Se*2	46.98	39.46	44.12
Cu	401.09	345.59	377.30	V	357.00	342.80	350.40
Hg*1	2.20	2.20	2.20	Zn	506.40	402.60	473.60
Mn	434.50	392.80	420.20	Zr	350.82	377.00	360.92

*1 95 of per cent of Hg enters the atmosphere as a vapor (9,19,48).

*2 60 of per cent of Se enters the atmosphere as a vapor (9,19).

5 EMISSION OF TRACE METALS FROM COAL-FIRED POWER PLANTS

The trace metal emission during coal combustion can be calculated using equation:

$$E = P \cdot e_f \cdot (1 - C_c \cdot C_t) \cdot S \qquad (3)$$

where:

- E = the trace metal emissions, mg of metal/day
- e_f = the emission factors (uncontrolled), kg of dust/1 tonne of coal
- P = daily coal requirements tonnes of coal/day
- C_c = the average operating efficiency of control equipment for each metal
- C_t = the fraction of the production capacity on which control equipment has been installed
- S = concentrations of trace metals in stack dust emitted during coal combustion, mg of metal/kg of dust.

Table 10 lists data on e_f, C_t and C_c for different boilers, assuming ESP installations with efficiency of 99 of per cent (43).

Table 10: Values of e_f, C_c and C_t for different boilers ESP equipped.

Boiler	e_f^{*1} kg of dust/ 1 tonnes of coal	C_c	C_t	$C_c \times C_t$
Cyclone	13.64	0.99	0.71	0.70
Stoker	59.09	0.99	0.87	0.86
Pulverized	72.73	0.99	0.97	0.96

*1 Assuming 10% of ash in coal. For another ash contents factor e_f can be calculated using equations (43):

$$e_f = 1.364 \times A \quad \text{for cyclone} \qquad (4)$$

$$e_f = 5.909 \times A \quad \text{for stoker} \qquad (5)$$

$$e_f = 7.273 \times A \quad \text{for pulverized} \qquad (6)$$

where:

A is content of ash, %

Using data from Tables 2,9 and 10, the trace metal emissions can be calculated. Table 11 presents data on trace metal emissions from different boilers, burning several types of coal, with 10 of per cent of ash, in a 100 MWe ESP-equipped power plant.

Table 11: Trace metal emission from a 100 MWe power plant, ESP equipped (g/day).

Element	Bituminous			Subbtuminous			Lignite		
	Cyclone	Stoker	Pulverized	Cyclone	Stoker	Pulverized	Cyclone	Stoker	Pulverized
As	204.0	242.4	137.2	247.3	293.8	166.2	343.8	408.4	231.1
Be	21.3	31.8	14.1	25.8	38.5	17.1	35.8	53.5	23.7
Cd	62.8	75.2	43.7	76.2	91.1	53.0	106.0	126.7	73.6
Co	384.0	443.1	218.3	465.5	537.1	264.6	647.0	746.5	367.8
Cr	1033.4	1726.5	731.8	1252.6	2092.6	887.1	1741.2	2908.7	1233.0
Cu	812.4	1415.0	543.3	984.8	1715.1	658.6	1368.8	2384.0	915.4
Hg*1	4.5	9.0	3.2	5.4	10.9	3.8	7.5	15.2	5.3
Mn	880.1	1608.5	605.1	1066.8	1949.7	733.5	1482.8	2710.1	1019.5
Mo	264.9	366.9	165.3	321.1	444.7	200.4	446.4	618.2	278.5
Ni	1299.2	2098.3	834.1	1574.8	2543.3	1010.9	2189.0	3536.0	1405.3
Pb	736.3	1110.6	473.2	892.5	1346.1	573.6	1240.5	1871.1	797.3
Sb	121.1	198.4	80.3	146.8	240.5	97.4	204.1	334.3	135.3
Se*2	95.2	161.6	63.5	115.3	195.9	77.0	160.3	272.3	107.0
V	723.1	1403.8	504.6	876.5	1701.5	611.6	1218.3	2365.1	850.1
Zn	1025.7	1648.7	682.0	1243.3	1998.3	826.7	1728.2	2777.7	1149.1
Zr	710.6	1543.8	519.7	861.3	1871.3	630.0	1197.2	2601.0	875.7

*1 only 5 of per cent of the total Hg emission

*2 only 40 of per cent of the total Se emission.

For other units (i.e., 350,700 or 2100 MWe) changing ESP efficiences and ash contents (i.e., 5,15 or 20 of per cent) the results in Table 11 can be estimated from Tables 2 and 10. It was also assumed for the calculation listed in Table 11 that precipitator efficiency for individual metals was as shown in Table 12 (27,28,29,46).

Table 12: Precipitator efficiency for individual metals.

Metal	Efficiency %	Metal	Efficiency %	Metal	Efficiency %
As	98.0	Hg*1	-	Sb	97.0
Be	98.0	Mo	99.0	Se	40.0
Cd	98.0	Mn	99.0	V	99.5
Co	99.7	Ni	99.7	Zn	99.0
Cr	99.9	Pb	97.0	Zr	99.5
Cu	98.0				

*1 Only 5 of per cent of Hg is emitted with particulate matters (9,19,48).

Emission of trace metals from power plants with wet scrubbers varies with the individual metals. On the basis of literature data (9,47) it was found that only Cr and Se emissions from wet scrubbers exceeds emissions from ESPs. Particular data are available from Table 13.

Table 13: Ratio of trace metal emissions from wet scrubber to emissions from ESP (9,47).

Element	Wet scrubber / ESP	Element	Wet scrubber / ESP	Element	Wet scrubber / ESP
As	0.32	Hg	-	Sb	0.58
Be	0.47	Mo	0.31	Se	1.90
Cd	0.46	Mn	0.48	V	0.21
Co	0.064	Ni	0.14	Zn	0.11
Cr	1.03	Pb	0.35	Zr	0.05
Cu	0.41				

Table 14 presents data on trace metal emissions from different boilers, burning several types of coal with 10 per cent ash in a 100 MWe wet scrubber-equipped power plant.

Table 14: Trace metal emission from a 100 MWe power plant, wet scrubber equipped (g/day).

Element	Bituminous			Subbituminous			Lignite		
	Cyclone	Stoker	Pulverized	Cyclone	Stoker	Pulverized	Cyclone	Stoker	Pulverized
As	65.3	77.6	43.9	79.1	94.0	53.2	110.0	130:7	74.0
Be	10.0	15.0	6.6	12.1	18.1	8.0	16.8	25.2	11.1
Cd	28.9	34.6	20.1	35.1	41.9	24.4	48.8	58.3	33.9
Co	24.6	28.4	14.0	29.8	34.4	16.9	41.4	47.8	23.5
Cr	1064.4	1778.3	753.8	1290.2	2155.4	913.7	1793.4	2996.0	1270.0
Cu	333.1	580.2	227.8	403.8	703.2	270.0	561.2	977.4	375.3
Hg	Not analysed								
Mn	422.5	772.1	290.5	512.1	935.9	352.1	711.7	1300.9	489.4
Mo	82.1	113.7	51.2	99.5	137.9	62.1	138.4	191.6	86.3
Ni	181.9	293.8	116.8	220.5	356.1	141.5	306.5	495.0	196.7
Pb	257.7	388.7	165.6	312.4	471.1	200.8	434.2	654.9	279.1
Sb	70.2	115.1	46.6	85.1	139.5	56.5	118.4	193.9	78.5
Se*1	180.9	307.0	120.6	219.1	372.2	146.3	304.6	517.4	203.3
V	151.9	294.8	106.0	184.1	357.3	128.4	255.8	496.7	178.5
Zn	112.8	181.4	75.0	136.8	219.8	90.9	190.1	305.6	126.4
Zr	35.5	77.2	26.0	43.1	93.6	31.5	59.9	130.1	43.8

*1 only 40 of per cent of total Se emission (9,19).

For other capacities, efficiencies of wet scrubbers and ash contents data from Table 14 can be obtained adequately from Tables 2 and 11.

On the basis of results showed in Tables 11 and 14, the emission factors of trace metals are calculated. Tables 15 and 16 present the trace metal emission factors (trace metal emissions for 1 MJ of energy produced for ESP and wet scrubber-equipped plants).

Table 15: Emission factors of trace metals (µg/MJ)[*1]
Dedusting installation: ESP.

Element	Bituminous			Subbtuminous			Lignite		
	Cyclone	Stoker	Pulverized	Cyclone	Stoker	Pulverized	Cyclone	Stoker	Pulverized
As	23.6	28.1	15.9	28.6	34.0	19.2	39.8	47.3	26.7
Be	2.5	3.7	1.6	3.0	4.5	2.0	4.1	6.2	2.7
Cd	7.3	8.7	5.1	8.8	10.5	6.1	12.3	14.7	8.5
Co	44.4	51.3	25.3	53.9	62.2	30.6	74.9	86.4	42.6
Cr	119.6	199.8	84.7	145.0	242.2	102.7	201.5	336.7	142.7
Cu	94.0	163.8	62.9	114.0	198.5	76.2	158.4	275.9	105.9
Hg[*2]	0.5	1.0	0.4	0.6	1.3	0.4	0.9	1.8	0.6
Mn	101.9	186.2	70.0	123.5	225.7	84.9	171.6	313.7	118.0
Mo	30.7	42.5	19.1	37.2	51.5	23.2	51.7	71.5	32.2
Ni	150.4	242.9	96.5	182.3	294.4	117.0	253.4	409.3	162.6
Pb	85.2	128.5	54.8	103.3	155.8	66.4	143.6	216.6	92.3
Sb	15.0	23.0	9.3	17.0	27.8	11.3	23.6	38.7	15.7
Se[*3]	11.0	18.7	7.3	13.3	22.7	8.9	18.5	31.5	12.4
V	83.7	162.5	58.4	101.4	196.9	70.8	141.0	273.7	98.4
Zn	118.7	190.8	78.9	143.9	231.3	95.7	200.0	321.5	133.0
Zr	82.2	178.7	60.1	99.7	216.6	72.9	138.6	301.0	99.3

[*1] The rest of assumptions as in Table 11.

[*2] Emission factors of Hg presented in Table 15 are 5 of per cent of total Hg emission factor (9,19,48).

[*3] Emission factors of Se presented in Table 15 are 40 of per cent of total Se emission factor (9,14).

Table 16: Emission factors of trace metals (µg/MJ)[*1]
Dedusting installaation: Wet scrubber.

Element	Bituminous			Subbtuminous			Lignite		
	Cyclone	Stoker	Pulverized	Cyclone	Stoker	Pulverized	Cyclone	Stoker	Pulverized
As	7.6	9.0	5.1	9.2	10.9	6.2	12.7	15.1	8.6
Be	1.2	1.7	0.8	1.4	2.1	0.9	1.9	2.9	1.3
Cd	3.3	4.0	2.3	4.1	4.8	2.8	5.6	6.7	3.9
Co	2.8	3.3	1.6	3.4	4.0	2.0	4.8	5.5	2.7
Cr	123.2	205.8	87.2	149.3	249.5	105.7	207.6	346.8	147.0
Cu	38.5	67.1	25.8	46.7	81.4	31.2	64.9	113.1	43.4
Hg				Not analyzed					
Mn	48.9	89.4	33.6	59.3	108.3	40.7	82.4	150.5	56.6
Mo	9.5	13.2	5.9	11.5	16.0	7.2	16.0	22.2	10.0
Ni	21.0	34.0	13.5	25.5	41.2	16.4	35.5	57.3	22.8
Pb	29.8	45.0	19.2	36.2	54.5	23.2	50.2	75.8	32.3
Sb	8.1	13.3	5.4	9.8	16.1	6.5	13.7	22.4	9.1
Se[*2]	20.9	35.5	14.0	25.4	43.1	16.9	35.2	59.9	23.5
V	17.6	34.1	12.3	21.3	41.3	14.9	29.6	57.5	20.7
Zn	13.1	21.0	8.7	15.8	25.4	10.5	22.0	35.4	14.6
Zr	4.1	8.9	3.0	5.0	10.8	3.6	6.9	15.1	5.1

[*1] The rest of assumptions as in Table 14

[*2] Emission factors of Se presented in Table 16 are 40 of per cent of total Se emission factor (9,19).

6 CONCLUDING REMARKS

The emission factors, calculated in the previous section, will be used to estimate the national emissions and their spatial distribution in European countries. This will require further information to be collected from thermal power plants. The information should satisfy certain requirements with respect to consisting between countries, and compatibility with available statistical data.

The emission factors obtained will be used together with available statistical data to provide an estimated emission field, corresponding as closely as possible to the EMEP emission survey for trace metals.

7 REFERENCES

(1) Babcock and Wilcox Co. — Steam, its generation and use, 38th ed., New York, 1972.

(2) Locklin, D.W. et al. — Power plant utilization of coal. Battelle energy program report, Battelle-Columbus Laboratories, Columbus, Ohio, 1974, 96 pp.

(3) Southern Research Institute — Survey of information of fine particle control. EPRI-259, PB 242 383, Palo Alto, C, 1975.

(4) Dvorak, A.J. et al. — The environmental effects by using coal for generating electricity. NUREG-0252. Argonne National Laboratory, Argonne, IL, 1977, 221 pp.

(5) Ottmers, D.M. Lowell, P.S. Noblett, J.G. — Energy and water requirements for air quality control. In: *Water management by the electric power industry. water resources symposium. No. 8*, Univ. of Texas, Austin, TX, 1975, pp. 358-370.

(6) Dvorak, A.J. Lewis, B.G. — Impacts of coal-fired power plants on fish wildlife and their habitats, Wash. D.C., U.S. Dept. of incerior, 1978, Rept. FWS/OBS-78/29, 260 pp.

(7) American Society for Testing and Materials — Standard specifications for classification of coals by rank, ASTM designation D388-66, reapproved 1972, In: *Gaseous fuels, coal and coke, Atmospheric analyses*, Part 26, 1973.

(8) Simon, J.A. Hopkins, M.E. — Geology of coal. In: *Elements of Practical Coal Mining*. Ill. State Geolog. Surv. Reprint, 1973.

(9) Pacyna, J.M.

Coal-fired power plants as a source of environmental contamination by trace metals and radionuclides, Habilitation thesis, Wrockaw (Poland), Technical University of Wrockaw, 1980, pp. 169.

(10) Goldschmidt, W.M.

Rare elements in coal ashes. *Ind. and Eng. Chem.* 27, 1100-1102 (1935).

(11) Nicholls, G.C.

The geochemistry of coal-bearing strate. In: *Coal and coal-bearing strata*, American Elsevier, New York 1968, pp. 269-307.

(12) Gluskoter, H.J.

Mineral matter and trace elements in coal. In: *Trace elements in fuel* Babu, Ed. 1975 Advances in Chemistry Series, Washington DC, pp. 1-22.

(13) Kuhn, J.K.
Fiene, F.L.
Cahill, R.A.
Gluskoter, H.J.
Shimps, N.F.

Abundance of trace and minor elements in organic and mineral fractions of coal. Illinois Institute of Natural Resources, Environ. Geology Notes 88, 1980, pp 67.

(14) Zubovic, P.

Physiochemical properties of certain minor elements as controlling factors of their distribution in coal, Washington D.C. 1966, (Advances in Chemistry Series 66) pp 221-246.

(15) Gluskoter, H.J.
Ruch, R.R.
Miller, W.G.
Cahill, R.A.
Dreher, G.B.
Kuhn, J.K.

Trace elements in coal; occurrence and distribution, Illinois State Geological Survey, Circular 499, Urbana, IL, 1977, pp 153.

(16) Roy, W.R.
Thiery, R.G.
Schuller, R.M.
Suloway, J.J.

Coal fly ash, a review of the literature and proposed classification system with emphasis on environmental impacts, Illinois Institute of Natural Resources, Environ. Geology Notes 96, 1981, pp. 69.

(17) Klein, D.H.
Andren, A.W.
Carter, J.A.
Emery, J.F.
Feldman, C.
Fulkerson, W.
Lyon, W.S.
Ogle, J.C.
Talmi, Y.
Van Hook, R.J.
Bolton, N.

Pathways of thirty-seven trace elements through coal-fired power plant. *Environ. Sci. Technol.* 9, 973-979 (1975).

(18) Bertine, K.K.
Goldberg, E.D.

Fossil fuel combustion and the major sedimentary cycle. *Science* 173, 233-235 (1971).

(19) Kaakinen, J.W.
Jorden, R.M.
Lawasani, M.H.
West, R.E.

Trace element behavior in coal-fired power plant. *Environ. Sci. Technol.* 9, 862-863 (1975).

(20) Lee, R.E.
Lehmden, D.J.

Trace metal pollution in the environment. *J. of Air Poll. Contr. Ass.* 23, 853-857 (1973).

(21) Murthy, K.S.
Howes, J.E.
Nack, H.

Emissions from pressurized fluidized - bed combustion processes. *Environ. Sci. Technol.* 13, 197-204 (1979).

(22) Block, Ch.
Dams, R.

Study of fly ash emission during combustion of coal. *Environ. Sci. Technol.* 10, 1011-1017 (1976).

(23) Coles, D.G.
Ragaini, R.C.
Ondov, J.M.
Fisher, G.L.
Silberman, D.
Prentice, B.A.

Chemical studies of stack fly ash from coal-fired power plant. *Environ. Sci. Technol.* 13, 455-459. (1979).

(24) Capes, C.E.
McIlhinney, A.E.
Russell, D.S.
Sirianni, A.F.

Rejection of trace metals from coal during benefication by agglomeration. *Environ. Sci. Technol.* 8, 35-38 (1974).

(25) Holland, W.F.
Wilde, K.A.
Parr, J.L.
Lowell, P.S.
Pohler, R.F.

The Environmental effects of trace elements in the pond disposal of ash and flue gas desulfurization sludge, EPRI Report, Palo Alto C, 1975, 49 pp.

(26) Rottman, H.K.
Kary, R.E.
Hudgins, T.

Ecological distribution of trace elements emitted by coal-burning power generating units employing scrubbers and electrostatic precipitators. In: *Fourth Symposium on Coal Utilization*. National Coal Association/Bituminous Coal Research, Inc. 1977, 192-215.

(27) Bolton, N.E.
Carter, J.A.
Emery, J.E.
Feldman, C.
Fulkeson, W.
Hulett, U.D.
Lyon, W.S.

Trace element mass balance around a coal-fired steam plant.
In: *Trace elements in fuel*, Babu, Ed., 1975 Advances in University Series, Washington DC, pp. 175-187.

(28)

Kolets hälso- och miljöeffekter, Prosjekt KHM, Lägesrapport, oktober 1981, pp 391.

(29) Ensor, D.S.
Cowen, S.
Shendrikar, A.
Markowski, G.
Woffinden, G.

Kramer station fabric filter evaluation. Palo Alto, Cal. 1981 (EPRI Report CS-1669.)

(30) Flagan, R.G.
Friedlander, S.K.

Particle formation in pulverized coal combustion - a review.
In: *Proceedings of the symposium on aerosol sicence and technology of the 82nd National Meeting of the American Institute of Chemical Engineers*, Atlantic City, 1976.

(31) Kaakinen, J.W.

Trace element study on a pulverized coal-fired power plant, PhD dissertation, Chem. Eng. Dept. University of Colorado, 1979.

(32) Davison, R.L.
Natusch, D.F.S.
Wallace, J.R.
Evans, Ch. A. Jr.

Trace elements in fly ash. Dependence of concentration on particle size. *Environ. Sci. Technol.* 8, 1100-1113 (1974).

(33) Coles, D.G.
Ragaini, R.C.
Ondov, J.M.
Fisher, G.L.
Silberman, D.
Prentice, B.A.

Chemical studies of stack fly ash from a coal-fired power plant. *Environ. Sci. Technol.* 13, 455-459 (1979).

(34) Torrey, S. ed.

Trace contaminants from coal. Noyes Data Corporation, 1978, (Pollution technology review No. 50) pp 294.

(35) Smith, R.D.
Campbell, J.A.
Felix, W.D.

Atmospheric pollutants from coal combustion.
In: *Elements in coal and potential environment concerns arising from those elements*, Society of Mining Engineers of AJME, Min. Symposium Series No. 79-06, 1979, pp 39.

(36) Smith, R.D.
Campbell, J.A.
Nielson, K.K.

Concentration dependance upon particle size of volatilized elements in fly ash. *Environ. Sci. Technol.* 13 553-558 (1979).

(37) Swaine, D.J.

Trace elements in coal.
In: *Trace substances in environmental health*, XI, D.D. Hemphill, ed. 1977, p. 107.

(38) Campbell, J.A.
Laul, J.C.
Nielson, K.K.
Smith, R.D.

Separation and chemical characterization of finely-sized fly ash particles. *Anal. Chem.* 50, 1032-1040 (1978).

(39) Smith, R.D.
Campbell, J.A.
Nielson, K.K.

Characterization and formation of submicron particles in coal-fired plants. *Atmos. Environ.* 13, 607-617 (1979).

(40) Natusch, D.F.S.
Wallace, J.R.
Evans, C.A. Jr.
Toxic trace elements; preferential concentration in respirable particles. *Science* 183, 202-204 (1974).

(41) Lee, R.E.
Crist, H.L.
Riley, A.E.
MacLeod, K.E.
Concentration and size of trace metal emissions from a power plant, a steel plant and a cotton yin. *Environ. Sci. Technol.* 9, 643-647 (1975).

(42) Hamersma, J.W. et.al.
JERL-RTP Procedures Manual: Level 1 Environmental Assessment, U.S.Environmental Protection Agency, Washington DC, 1976, (EPA-600/2-76-160a) pp. 29-46.

(43)
Particulate Pollutant System study. Vol. 1 - Mass emissions, MRI, Project No. 3326-C, Durham, NC, 1971.

(44)
Particulate Pollutant System Study. Vol II - Fine particle emissions, MRI, Project No. 3326-C, Durham, NC,1971.

(45)
Particulate Pollutant System Study. Vol III - Handbook of emission property, MRI, Project No. 3326-C, Durham, NC, 1971.

(46) Ensor, D.S.
Cowen, S.
Hooper, R.
Markowski, G.
Evaluation of the George Neal No. 3 Electrostatic Precipitator, Palo, Alto, Cal. 1979, EPRI, Report FP-1145.

(47) Ondov, J.M.
Ragaini, R.C.
Bierman, A.H.
Elemental emissions from a coal-fired power plant. Comparison of a venturi wet scrubber system with a cold-side electrostatic precipitator. *Environ. Sci. Technol.* 13, 588-601 (1979).

(48) Billings, C.E.
Sacco, A.M.
Matson, W.R.
Griffin, R.M.
Coniglio, W.R.
Harley, R.A.
Mercury balance on a large pulverized coal-fired furnace. *J. of the Air Poll. Contr. Ass.* 23, 773-777 (1973).

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ABSTRACT (max. 300 characters, 5-10 lines)
The emission factors of trace metals are established for different types of power stations, using enrichment factors of these pollutants in the flue gas stream and technological data of boilers and dedusting installastions.
Major physical components and coal requirement for coal-fired power plant are presented. The emission factors obtained, will be used to estimation of the national emissions and their spatial distribution in European countries.

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III